

MAGNETIC BRAKING REVISITED

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ABSTRACT

We present a description for the angular momentum loss rate due to magnetic braking for late type stars taking into account recent observational data on the relationship between stellar activity and rotation. The analysis is based on an idealized two component coronal model subject to constraints imposed on the variation of the coronal gas density with rotation period inferred from the observed variation of X-ray luminosity, L_x , with rotation rate, Ω , ($L_x \propto \Omega^2$) for single rotating dwarfs. An application of the model to high rotation rates leads to a gradual turnover of the X-ray luminosity which is similar to the saturation recently observed in rapidly rotating dwarfs. The resulting angular momentum loss rate, \dot{J} , depends on Ω in the form $\dot{J} \propto \Omega^\beta$ where $\beta \sim 3$ for slow rotators and ~ 1.3 for fast rotators. The relation at high rotation rates significantly differs from the power law exponent for slowly rotating stars, depressing the angular momentum loss rate without necessarily requiring the saturation of the magnetic field. The application of this model to the evolution of cataclysmic variable binary systems leads to mass transfer rates that are in approximate accord with those observed in comparison to rates based on either a Skumanich law or an empirical law based on $\beta = 1$.

Subject headings: binary:close – binary:magnetic braking – binary:rotation – stars:late-type

1. INTRODUCTION

It is generally accepted that the angular momentum removed from a stellar surface by the action of a magnetically coupled stellar wind is important in studies of the formation and evolution of close binary systems. Magnetic braking (MB) is thought to be the fundamental mechanism responsible for orbital angular momentum loss in a number of classes of close binaries, such as cataclysmic variables (CVs) and low mass X-ray binaries (LMXBs). For such systems, MB has two important roles. It provides a mechanism for promoting mass transfer from the low mass donor to its more massive compact companion. In addition, it determines the range of post common envelope orbital separations for which the system evolves into this mass transfer stage.

MB was first suggested as a mechanism for removing angular momentum from single stars by Schatzman (1962), who noticed that slowly rotating stars have convective envelopes. A key insight was his recognition that material lost from the stellar surface is kept in corotation with the star by the magnetic field, leading to the result that the specific angular momentum carried by the gas is significantly greater than in a spherically symmetric stellar wind. To maintain corotation, a star should possess a substantial magnetic field. This can be achieved in low-mass main sequence (MS) stars by gas motions in the deep convective envelope, leading to the generation of a magnetic field by dynamo action.

Evidence for angular momentum loss in single stars is provided by the observations of young low-mass T Tauri stars which have shown that the stellar angular momentum is significantly higher in the pre-MS stage than in the MS stage for stars of similar masses (Stauffer & Hartmann 1987). In addition, the observations of rotational velocities of stars in young clusters show a high rate of angular momentum loss. Specifically, the K-dwarfs in the Hyades (age $\approx 6 \times 10^8$ yr) have mean rotational velocities below 10 km s^{-1} , but stars of the same spectral type in the Pleiades (age $\approx 7 \times 10^7$ yr) have mean rotational

velocities of about 40 km s^{-1} (Stauffer 1987). These observations supplemented the early work of Skumanich (1972) who showed that the equatorial rotation velocities of G type MS stars decrease with time, t , as $t^{-0.5}$. We note that this empirical dependence, upon which many studies are based, was established for stars with velocities in the range of 1 to 30 km s^{-1} , but its applicability to the MS-like companion stars in close binaries of short orbital period (where rotational velocities are $\gtrsim 100 \text{ km s}^{-1}$) is suspect.

In parallel to these observational developments, many theoretical efforts were undertaken to understand the angular momentum loss mechanism over a wide range in rotation rates. For example, the Skumanich relation for slowly rotating stars can be reproduced by an angular momentum loss rate, \dot{J} , proportional to Ω^3 , where Ω is the stellar rotational angular velocity, for a thermally driven stellar wind. In this case, the magnetic field is assumed radial and to vary linearly with Ω (Weber & Davis 1967). For fast rotation, a wide variety of theoretically predicted laws in the form $\Omega \propto t^{-\alpha}$ are possible with α ranging from 0.5 to 4 (Mestel 1984). More recently, Kepens, MacGregor, & Charbonneau (1995) considered a polytropic magnetized solar wind within the framework of a model developed by Weber & Davis (1967) showing that the angular momentum loss rate is consistent with the Skumanich law at low angular velocities, but the power law dependence is shallower asymptotically approaching $\dot{J} \propto \Omega^2$ at high angular velocities due to centrifugal effects. Additional factors affecting the angular momentum loss have been pointed out by Mestel & Spruit (1987, hereafter MS87) who showed that, in a two-component model, more gas is confined in a dead zone, which does not contribute to the braking, at high angular velocities.

To further complicate the picture, significant observational developments have increased the disparity between observations and interpretations based on the Weber-Davis type prescription (for a review see Collier Cameron

2002). In particular, the observations of stars in open clusters have shown that the Skumanich law overestimates the spin down rate to an age of about 10^8 yr and, thus, does not explain the presence of fast rotators in the Pleiades (Stauffer 1987; Andronov et al. 2003). As a possible resolution to this problem, MacGregor & Brenner (1991) suggested that magnetic braking is reduced at high rotation rates due to the possible saturation of a stellar dynamo resulting in an angular momentum loss rate proportional to Ω . Here, the strength of magnetic field at the stellar surface becomes independent of the angular velocity in the convective zone at high rotation rates. The saturation regime is normally considered to occur at rotational rates of about $10\Omega_\odot$, where Ω_\odot is the angular velocity of the Sun. While the magnetic field strength in active regions of the Sun is a few orders of magnitude higher than the average, the fundamental reason for saturation of the magnetic field at the rotational velocity which is only one order of magnitude higher than in the Sun is not understood. Another possible mechanism presumes that the depression of the rate of angular momentum loss may be related to the appearance of an increasingly complex field topology as the rotation rate increases leading to a reduction in the fraction of open field lines (e.g., Taam & Spruit 1989).

Observations of CVs also do not provide direct support for an angular momentum loss rate proportional to a linear function of the angular velocity (see Andronov et al. 2003). The empirically determined mass transfer rates in CVs have been estimated to follow the relation

$$\log \dot{M} = 3.3 \log P_h - 11.2 \pm 1, \quad (1)$$

where \dot{M} is the mass transfer rate in $M_\odot \text{ yr}^{-1}$ and P_h is the binary orbital period in hours respectively (Patterson 1984). Although the inferred mass transfer rates are somewhat uncertain, they lie systematically higher than one predicts from the application of the angular momentum loss rate associated with saturated magnetic braking.

It is therefore clear that there is further need to investigate MB for fast rotators. Accordingly, we attempt to provide additional insight into the angular momentum loss rate associated with the MB process in the context of the idealized MS87 model in conjunction with recent observations for the X-ray emission of rotating dwarfs (Pizzolato et al. 2003). With these observational constraints, we present a modified angular momentum loss description and apply it to evolutionary calculations in a CV-type close binary system. In §2, the model is described and its application to the evolution of CVs is presented. We summarize our results and discuss the possible implications of the modified angular momentum loss rate in the final section.

2. MODEL OF MB

We consider MB within the framework of the two-component model described in MS87. In contrast to the earlier model described by Weber & Davis (1967), a dipole magnetic field, in addition to a radial field, and centrifugal acceleration effects on the wind are included. The strong field regions of this dipole field are envisioned to confine hot plasma in a corotating dead zone (Mestel 1968). Although the X-ray emitting corona is largely pro-

duced by matter confined in loops (Vaiana, Krieger, & Timothy 1973) which fluctuate greatly in the Sun's magnetosphere (Sheeley & Golub 1979; Shimizu & Tsuneta 1977), we shall assume that the average behavior in this time dependent structure can in the lowest order be approximated by a steady hydrostatic dead zone model. Partial support for such a simple two-component coronal structure is provided by the observations taken during solar eclipse using the *Skylab* telescope and *Yohkoh* X-ray satellite. Since the matter in the dead zone is trapped within the magnetosphere and is not lost in the wind, the efficiency of MB in this idealized model is reduced in comparison to other idealized theoretical models without such regions. The dipole field in the model is assumed to be closed up to a cusp point that defines the radius of the dead zone, R_d . Beyond this point the magnetic field is assumed to be essentially radial. Recently, support for the large scale description of such a picture has been provided by the X-ray observations of the Sun obtained from the *Ulysses* mission. In particular, Li (1999) showed that the assumption of homogeneity in latitude of the wind flux and the radial magnetic field at large distances, a basic feature inherent in the model, is basically correct.

2.1. Constraints on the coronal density from L_x

It was noted in MS87 that the two-component magnetic field model should be consistent with the X-ray observations of single stars. Recent results by Pizzolato et al. (2003) confirm earlier results by Pallavicini et al. (1981), showing that the X-ray luminosity, L_x , is proportional to Ω^2 for slowly rotating stars. Since the X-ray emission is related to the coronal gas density in the dead zone, $\rho_{0,d}$, in this model, $\rho_{0,d}$ should be a function of Ω . In the simplest model consistent with the X-ray observations, MS87 considered the possibility that $\rho_{0,d}$ is linear in Ω . This choice was based on the assumption that the observed variation of coronal emission is determined primarily by the variation in density, that is, $L_x \propto \rho_{0,d}^2$ and, hence, $L_x \propto \Omega^2$, neglecting the weak dependence on coronal temperature. Such a picture is an oversimplification since the variation in X-ray luminosity not only reflects variations in the coronal gas density, but also the volume of the X-ray emitting zone.

Further compounding the validity of the linear relation between the coronal gas density and rotational angular velocity are the recent observations of X-ray emission from late-type dwarfs, which have shown that the relationship between the X-ray luminosity and rotation rate changes form at high rates (Pizzolato et al. 2003). In particular, the X-ray luminosity is found to be nearly independent of Ω for $\Omega \gtrsim \Omega_x \sim 2 - 12\Omega_\odot$ in the mass range of $0.22 - 1.29 M_\odot$. The qualitative change from $L_x \propto \Omega^2$ to L_x independent of Ω (for $\Omega > \Omega_x$) provides an important constraint on the MB model. In the following we make use of this observed trend to constrain the variation of $\rho_{0,d}$ with Ω in the MS87 model.

In order to estimate the X-ray luminosity from the MS87 model, we assume that the emitting region can be roughly identified with the dead zone in some spatially and time averaged sense. The radius of the dead zone is taken from eq. (8)_{MS} in MS87, where it is assumed that $\rho_{0,d} \propto \Omega^p$ and $B_0 \propto \Omega$. In addition, we

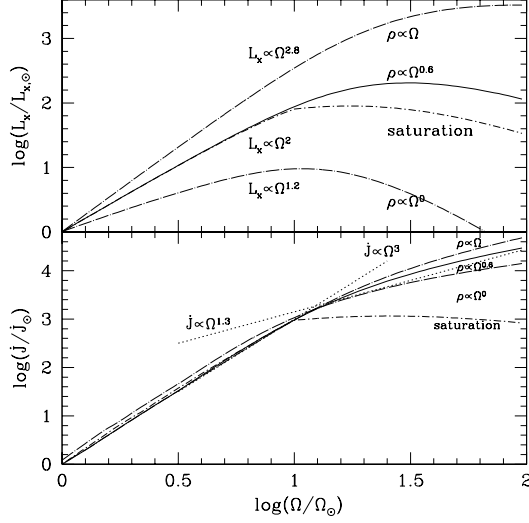


FIG. 1.— The variation of the X-ray luminosity and angular momentum loss rate for a $1 M_{\odot}$ star as a function of angular velocity. Upper panel: The variation of L_x , as a function of Ω . $L_{x,\odot}$ corresponds to L_x at $\Omega = \Omega_{\odot}$. The thick solid line represents the solution for which $\rho \propto \Omega^{0.6}$. Thick dash-dotted line represent the solution for the same density variation but with the saturation of the magnetic field at $\Omega \geq 10 \Omega_{\odot}$. The upper and lower thin dash-dotted lines show L_x for $\rho \propto \Omega^0$ and $\rho \propto \Omega$ respectively. Lower panel: The variation of J , as a function of Ω . J_{\odot} corresponds to the rate of the angular momentum loss for the star rotating with $\Omega = \Omega_{\odot}$. Lines as described for the upper panel.

assume that the parameter $\zeta_d = B_0^2 / 8\pi\rho_{0,d}a_d^2$ is equal to 60 where a_d is the sound speed in the dead zone (see MS87). For a solar type star of mass, M , equal to $1 M_{\odot}$ the parameter p was varied such that the L_x varied with Ω in approximate accordance to the observed relationship, with a normalization chosen to correspond to the solar X-ray luminosity at Ω_{\odot} . The functional form of L_x with respect to Ω was found to be very sensitive to p for $\Omega \lesssim 10 \Omega_{\odot}$, varying as $\Omega^{1.2}$ and $\Omega^{2.8}$ for p equal to 0 and 1 respectively. The relation between L_x and Ω is illustrated in the upper panel of Fig. 1, where the best fit for $L_x \propto \Omega^2$ corresponds to $p \approx 0.6$.

Fig. 1 also reveals that L_x is relatively insensitive to angular velocity at high angular velocities, especially for $p \gtrsim 0.6$. This tendency toward saturation occurs at high rotation rates since the centrifugal effects become increasingly important, resulting in the shrinkage of the dead zone (MS87). The decrease in volume tends to offset the increase in $\rho_{0,d}$ as Ω is increased resulting in a nearly constant value for L_x . For this model, L_x actually decreases for sufficiently large Ω . At larger values of p , L_x increases monotonically since the density dependence more than compensates for the reduction in emitting volume. On the other hand, the volume effect is more important for smaller values of p , leading to a significant reduction in L_x as Ω is increased.

The ratio of L_x^{sat} in the saturated regime, taken to correspond to the maximum value of L_x , to $L_{x,\odot}$ at $\Omega = \Omega_{\odot}$ for $p = 0.6$ is in approximate accord to that observed. Specifically, $\Delta = \log L_x^{\text{sat}} / L_{x,\odot} = 2.3$ from the numerical results for $p = 0.6$ and $\Delta = 2.4$ from the observations (see Fig. 5 in Pizzolato et al. 2003). We point out that the

qualitative behavior of L_x as a function of Ω is insensitive to the adopted choice of ζ_d . Quantitatively, the detailed results only change slightly. For example, for $\zeta_d = 4$ (see MS87), $p \sim 0.4$ and $\Delta = 2.2$.

For comparison, we have also displayed the solution with a saturated magnetic field for $\Omega \geq 10 \Omega_{\odot}$ in Fig. 1. Although L_x is seen to turnover as well, we note that it occurs at a level significantly less than observed with $\Delta = 2$. We cannot exclude the possibility that saturation of the magnetic field takes place based on the observed relation $L_x(\Omega)$ since it may take place at rotation rates higher than $10 \Omega_{\odot}$ making it difficult to distinguish the influence of the saturation of the magnetic field from the influence of the variation of the dead zone with angular velocity. However, the X-ray observations of solar type stars alone do not require the additional assumption of a saturated magnetic field at high rotation rates.

2.2. MB rate

The transport of the angular momentum by the wind and by Maxwell stresses is equivalent to that found by assuming corotation maintained out to the Alfvén surface (Mestel 1984). The angular momentum loss rate can be written as

$$-\dot{J} = 4\pi\Omega \int_0^{\pi/2} (\rho_A v_A R_A^2) (R_A \sin \theta)^2 \sin \theta d\theta, \quad (2)$$

where θ is the polar angle, and ρ_A , v_A , and R_A are the density, velocity, and radius at the Alfvén surface respectively. By continuity, $\rho_A v_A / \rho_d v_d = B_A / B_d = (R_d / R_A)^2$ assuming a radial field beyond the dead zone region. Here the radius of the dead zone is found from equ. (8)_{MS} of MS87. Then

$$\begin{aligned} -\dot{J} &= 4\pi\Omega_{\odot} R_{\odot}^4 \rho_{d,\odot} v_{d,\odot} \left(\frac{v_d}{v_{d,\odot}} \right) \left(\frac{R}{R_{\odot}} \right)^4 \left(\frac{\Omega}{\Omega_{\odot}} \right)^{p+1} \\ &\int_0^{\pi/2} \left(\frac{R_A}{R} \right)^2 \left(\frac{R_d}{R} \right)^2 \sin^3 \theta d\theta \\ &= C_j \left(\frac{v_d}{v_{d,\odot}} \right) \left(\frac{R}{R_{\odot}} \right)^4 F \left(M, \frac{\Omega}{\Omega_{\odot}} \right). \end{aligned} \quad (3)$$

where R is the stellar radius and C_j incorporates all physical constants.¹ The Alfvén radius is found from equ. (14)_{MS} of MS87.

In the lower panel of Fig. 1, the angular momentum loss rate relative to the Sun, $\log(\dot{J}/\dot{J}_{\odot})$, is shown as a function of normalized angular velocity, Ω/Ω_{\odot} , for three different values of p corresponding to $p = 0, 0.6$ and 1 . For reference, we also illustrate the variation of the angular momentum loss rate for the case of a saturated magnetic field (for $\Omega > \Omega_x$) with $p = 0.6$. For slow rotation, the MB is consistent with the Skumanich law and

¹ $F(M, \Omega/\Omega_{\odot})$ also depends on the solar sonic velocity and the coronal density, but we treat them as constants in order to scale the equation to the observed value of the solar Alfvén radius and the dead zone. We are aware that $R_{A,\odot}$ and $R_{d,\odot}$ are not known precisely, and in particular are different in MS87 and Li(1999). Since we do not attempt to derive the precise value for the current solar \dot{J} directly from observations as in Li (1999), we adopted these values as in MS87 and assume that uncertainties in the measured solar values are absorbed in the calibration of \dot{J} .

is nearly independent of the dependence of the coronal density on angular velocity (in contrast to the variation of L_x with Ω). However for fast rotation ($\Omega \gtrsim 10\Omega_\odot$), $\dot{J} \propto \Omega^{1.3}$ for $p = 0.6$, the value inferred from the constraints based on the X-ray observations (see above). We note that the asymptotic form of the angular momentum loss rate on the angular velocity, in contrast to the X-ray luminosity, is insensitive to the value of p if p lies between 0.6 and 1. On the other hand, if the magnetic field is saturated, the angular momentum loss rate is approximately constant at high rotation rates. Hence, the loss rate from a centrifugally driven wind differs from the linear functional form suggested by MacGregor & Brenner (1991) for saturation of the stellar dynamo based on a thermally driven stellar wind model.

Based on these results, the solution for the rate of angular momentum loss due to MB can be presented in the parameterized form

$$-\dot{J} = K_j \left(\frac{R}{R_\odot} \right)^4 \left(\frac{T_d}{T_{d,\odot}} \right)^{1/2} \begin{cases} (\Omega/\Omega_\odot)^3, & \text{for } \Omega \leq \Omega_x \\ \Omega^{1.3} \Omega_x^{1.7} / \Omega_\odot^3, & \text{for } \Omega > \Omega_x \end{cases} \quad (4)$$

Here, the value of K_j depends on the mass of the star, and the temperature and density in the corona which can be derived directly from the observational data (Li 1999). This parametrized form is presented only to provide a more transparent form of the angular momentum loss rate for comparison between the magnetic braking law based on equ. 3 and the power law representations describing the Skumanich law (e.g., as in Verbunt & Zwaan 1981) or the saturated braking law (Andronov et al. 2003). In detailed calculations, the rate of angular momentum loss due to MB should be found using equ. 3 together with highly nonlinear equ. (8)_{MS} and equ. (14)_{MS} of MS87.

In this study we adopt the approach of calibrating K_j using evolutionary calculations to reproduce the known solar rotation period at the age of the Sun (see Kawaler 1988). For $\Omega_\odot = 3 \times 10^{-6}$ we find $K_j = 6 \times 10^{30}$ [dyn cm], which is about three times the value obtained in Li (1999) and about the same as in Pylyser & Savonije (1988) (their value includes a variable factor $0.73 < f < 1.78$). The corresponding value for the constant in the equ. (4) is $C_j = 2.1 \times 10^{27}$ [dyn cm].²

Our description of magnetic braking has been applied to a study of the rotational evolution of single stars for comparison to the observed spin-down of stars in young clusters. Although stellar rotation is not included in the stellar structure, we calculated two sets of stellar models of mass 1, 0.8 and 0.6 M_\odot with the chemical composition as in Pleiades and Hyades to obtain an indication of the effect of our modified braking rate. The models were evolved for a time corresponding to 7×10^7 yr for the Pleiades and 6×10^8 yr for the Hyades clusters. The initial surface rotational velocity was taken as the break-up velocity. The numerical results as presented in Table

² Our code does not incorporate the angular velocity in the equation of hydrostatic equilibrium and therefore a more accurate calibration can be carried out with an evolutionary code including the effects of rotation. However, since the value of K_j mainly depends on the evolution of a relatively slowly rotating star, where Ω does not contribute significantly to hydrostatic equilibrium, our results should be adequate.

TABLE 1. THE ROTATIONAL VELOCITIES OBTAINED FROM THE THEORETICAL MODELS AND FROM THE OBSERVATIONS FOR THE PLEIADES AND HYADES CLUSTERS, IN km s^{-1} . HERE, “OBSERVED” CORRESPONDS TO THE MAXIMUM OBSERVED VELOCITY OF STARS IN THE PLEIADES OR THE HYADES, “SATURATED” REPRESENTS THE RESULTS OF CALCULATIONS BASED UPON THE SATURATED MAGNETIC BRAKING LAW, AND “STANDARD” REPRESENTS THE MAXIMUM ROTATIONAL VELOCITY THAT CAN BE OBTAINED WITH THE STANDARD PRESCRIPTION FOR THE MAGNETIC BRAKING (ALL THE DATA IS TAKEN FROM ANDRONOV ET AL. 2003); “THIS WORK” REPRESENTS RESULTS OF THE SPIN-DOWN USING EQU.3.

cluster	velocity	$1.0M_\odot$	$0.8M_\odot$	$0.6M_\odot$
Pleiades	observed	60	50	100
	this work	70	95	140
	saturation	100	105	100
	standard	15	20	25
Hyades	observed	5	4	9
	this work	6	6	6
	saturation	6	7	9
	standard	6	6	8

1 show that the level of agreement between the observations and the angular momentum loss rate presented in this study and with the loss rate based on a saturated model is comparable. The agreement is good for the Pleiades cluster and is slightly better for stars of mass 1 and 0.8 M_\odot in comparison to the lower mass model for the Hyades cluster. Here, the observational data for $v \sin i$ and data for the spin-down based on the saturated magnetic braking law and the Skumanich law have been taken from Andronov et al. (2003).

2.3. Binary evolution

To determine the consequences of our modified angular momentum loss rate prescription on the evolution of a binary system, we calculated the mass transfer phases of two binary model sequences. The model stars are chosen to be of a solar metallicity. The first sequence consisted of 1 M_\odot evolved donor and the second a 0.8 M_\odot unevolved donor, both are on the MS and, with a 0.6 M_\odot white dwarf companion. Such types of systems can be considered to be representative of CVs. For the evolved donor, the central hydrogen abundance was $X = 0.35$. The radii of the evolved and unevolved model stars were such that they filled their Roche lobes at orbital periods of $P = 7.5$ h and 5.2 h respectively. To follow the evolution, we used the code described in Ivanova et al. (2003), supplemented with angular momentum loss rates associated with MB based on equ. (3). The evolution of the system is assumed to be non conservative with nearly all the mass lost from the donor³ ejected as a consequence of nova explosions or as a result of an optically thick wind from the white dwarf surface (Hachisu, Kato, & Nomoto 1999). For comparison, we also performed mass transfer sequences with MB according to Verbunt & Zwaan (1981) based on the Skumanich law (taken from Pylyser & Savonije, 1988).

The results for the mass transfer rates are shown as a function of orbital period in Fig. 2. The average mass transfer rate for both donors is $\sim 5 \times 10^{-10} M_\odot \text{ yr}^{-1}$. For comparison, we also display the mass transfer rates cor-

³ For details on the treatment in our code for the WD evolution and its ability to accumulate mass see Ivanova & Taam in preparation (see also Li & van den Heuvel 1997).

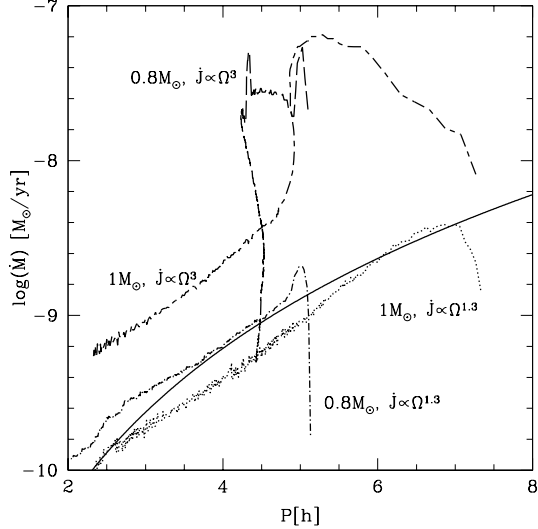


FIG. 2.— The variation of mass transfer rate (in $M_{\odot} \text{ yr}^{-1}$) as a function of orbital period (in hours) for two model sequences. The evolution of a $1 M_{\odot}$ evolved donor and $0.6 M_{\odot}$ white dwarf is illustrated by a dotted line for the angular momentum prescription presented in this paper and as a dash-dotted line for the angular momentum prescription assuming that the Skumanich law applies to high angular velocities. The dot-dashed and dashed line illustrate the evolution of a $0.8 M_{\odot}$ unevolved donor with a $0.6 M_{\odot}$ white dwarf with the prescription adopted here and the Skumanich law respectively. For reference, the solid line represents the empirically inferred mass transfer rates obtained by Patterson (1984).

responding to those observationally estimated according to an empirical relation obtained by Patterson (1984). It can be seen that the mass transfer rates promoted by the Skumanich law are generally higher than the empirical values, and the rates produced by the modified MB rate are in approximate agreement. The evolutionary timescale of the systems is increased by about a factor of 5 for the both sequences with the modified MB rate in comparison to the prescription based on the Skumanich law. We note that this is significantly less than the factor of 100 found by Andronov et al. (2003) in their case for MB rate based on $\dot{J} \propto \Omega$.

3. SUMMARY

The X-ray luminosity of late type stars and the angular momentum loss rate associated with magnetic braking of these stars has been examined in terms of an idealized two-component coronal model in the light of recent observational studies relating stellar activity to stellar rotation. By assuming that the X-ray luminosity can be used as a proxy for the coronal gas density in the magnetosphere we have, as a first step, constrained the two-component model to reproduce the observed variation of X-ray luminosity with stellar rotation ($L_x \propto \Omega^2$) for slowly rotating late type dwarfs. The application of this model to rapidly rotating dwarfs provides a qualitative explanation for the observed saturation at high rotation rates where the decrease in volume of the X-ray emitting coronal region nearly compensates for the increase in coronal gas density with increasing rotational velocity.

The angular momentum loss rate resulting from such a model has been analyzed and a parameterized form for the rate has been presented. In particular, it has the form

$\dot{J} \propto \Omega^3$ for slow rotators to reproduce the Skumanich law and $\dot{J} \propto \Omega^{1.3}$ for fast rotators ($\Omega > 10\Omega_{\odot}$). The angular momentum loss rate is more sensitive to Ω in the high rotation rate regime than the form, $\dot{J} \propto \Omega$, adopted in recent studies by Andronov et al. (2003). In addition, the reduction of the angular momentum loss rate from that based on the Skumanich relation for slowly rotating stars, required by the observation of rapidly rotating stars in clusters, can be accommodated without necessarily invoking the assumption that the magnetic field saturates at high rotation rates. We note, however, that the observations of rotational velocities of stars less massive than about $0.4 M_{\odot}$ (see Andronov et al. 2003 and references therein) suggest that the angular momentum loss rate is further weakened.

The modified form of the angular momentum loss rates can be applied to both LMXBs and CVs, and we have carried out binary evolutionary calculations for model systems representative of CVs as an illustration. It has been shown that the mass transfer rates are approximately consistent with those observed for CVs provided that the observed rates are accurate and reflect the long term secular values. The calculated rates for unevolved and evolved main sequence-like stars are found to be about an order of magnitude lower than rates obtained using angular momentum loss rates based on the application of the prescription for slowly rotating stars to the rapidly rotating stars in CVs and are higher by a factor of 10 than the rates obtained using rates obtained using a saturated braking law (Andronov et al. 2003). As a consequence the time scale for both the pre CV's to evolve into the CV phase and the evolution during the CV phase are increased in comparison to previous detailed binary evolutionary studies, but a factor of 10 shorter than obtained using a saturated law. Hence, the possibility that finite age effects are important in understanding the distribution of such systems (e.g., King & Schenker 2002; Andronov et al. 2003) is made less likely.

Although the mass transfer rates are significantly higher than that obtained by Andronov et al. (2003), the rates are a factor of 2 to 3 times lower than the rates ($\dot{M} > 1.5 - 2 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$) required to force an unevolved donor sufficiently out of thermal equilibrium to explain the period gap width in the disrupted magnetic braking model (see McDermott & Taam 1989; Kolb 2002). As noted previously, the upper boundary of the period gap at about 3 hours approximately corresponds to a main sequence star of $\sim 0.4 M_{\odot}$. However, there is no observational evidence indicating a discontinuous change in the rate of spin down of single stars, although, for less massive stars, the rotational velocity data of clusters suggests a further weakening of the angular momentum loss rate (see Sills, Pinsonneault, & Terndrup 2000). This suggests that other mechanisms should be sought to prevent systems from entering into the period gap. A possible alternative involves a period bounce first suggested by Eggleton (1983) involving additional angular momentum losses, perhaps, beyond that considered in the present study (see e.g., Taam, Sandquist, & Dubus 2003).

An additional consequence of the reduced angular momentum loss rate for rapidly rotating stars will be a revision of the binary orbital period delineating those sys-

tems which evolve to shorter periods (angular momentum loss dominated evolution) from those which evolve to longer orbital periods (nuclear evolution dominated). This period not only depends on the rate of angular momentum loss, but is also a function of the mass of the binary components and the degree to which mass is lost from the system. For the case of conservative mass transfer, Pylyser & Savonije (1988, 1989) estimate a bifurcation period of about 12 hours for systems with an accreting compact companion. With a reduced effectiveness of magnetic braking, it is expected that the transition will shift to shorter orbital periods.

Future phenomenological studies of the X-ray emission from late type stars and the angular momentum losses associated with magnetic braking in these stars are desirable to determine the explicit mass dependence on the

input parameters (magnetic field, density and temperature of the magnetically confined region) in the simplified magnetically coupled stellar wind models. The constraints imposed by both the X-ray studies and rotational velocity studies may provide insight into the further reduction of the angular momentum loss rates for stars less massive than $0.4 M_{\odot}$. The incorporation of these ideas in binary evolutionary sequences will be necessary in order to make meaningful comparisons between the observed and theoretically predicted CV period distributions in future population synthesis studies.

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